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COMBUSTION AND MICRO-EXPLOSION OF WATER/OIL EMULSIONS  
IN HIGH PRESSURE EN. (U) CALIFORNIA UNIV DAVIS DEPT OF  
MECHANICAL ENGINEERING C K LAW 11 MAR 86

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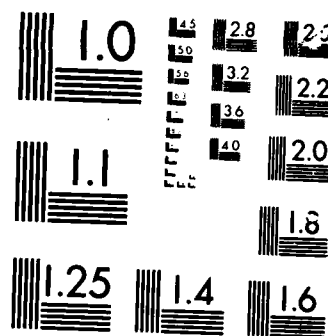
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20. Abstract continued

formation in droplet burning have been systematically assessed, and the ignition limits of fuel droplets vaporizing over a hot plate have been determined. Highlights of the specific accomplishments are separately summarized.

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FINAL REPORT

"Combustions and Micro-Explosion of Water/Oil Emulsions in  
High Pressure Environments"

Grant No. DAAG29-85-K-0010

Submitted to the

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## SUMMARY

During the reporting period we have accomplished all the objectives as stated in the proposal on gaining fundamental understanding in the combustion and micro-explosion properties of droplets of water/oil emulsions and miscible multicomponent fuel blends. Specifically, the gasification mechanisms of these multicomponent droplets have been unambiguously identified, the relative importance of the various physical and chemical factors influencing soot formation in droplet burning have been systematically assessed, and the ignition limits of fuel droplets vaporizing over a hot plate have been determined. Highlights of the specific accomplishments are separately summarized in the following.

## ACCOMPLISHMENTS

### 1. Development of the Phase-Discriminating Sampling Probe

A major difficulty which we encountered in our soot studies is the inability to separate out the soot formed in the gas from the heavy components and surfactants in the liquid emulsion. That is, by sampling and drying the entire combustion product including the droplets, the residue left on the filter paper includes both soot and the pyrolyzed heavy components. The weight of these pyrolyzed products overwhelms that of the soot.

To circumvent this difficulty, we have developed a phase-discriminating sampling probe which can separate out the liquid fuel, the gaseous fuel and product, and the soot. The principle involves inertia separation. That is, by applying a small suction of controlled intensity to a falling droplet, the gaseous species as well as the soot can be abstracted sideways into a sampling tube within which the soot is further separated out through filtering. The

indicates a mixed-mode behavior in that while the volatile components are not rapidly depleted from the droplet interior as required by the distillation mode, they also do not attain constant concentrations as required by the diffusion-limited mode. Theoretical calculations then reveal that liquid-phase mass diffusion is not as slow as previously thought, implying that the volatile components can still be continuously supplied to the droplet surface to be preferentially gasified, albeit at a slow rate.

Additional experiments have also been conducted for droplets undergoing pure vaporization in a relatively cold environment, say around  $600^{\circ}\text{C}$ . Since the droplets now regress relatively more slowly, mass diffusion is facilitated such that gasification now resembles batch distillation.

Finally, we have also experimented with water/oil emulsion droplets. Since the water micro-droplets basically do not diffuse, the mass diffusivity can be considered to be zero. In this limit the droplet composition does reach steady state as required by the theory.

This work is reported in publication No. 1.

### 3. Physical Mechanisms on Soot Formation in Droplet Burning

Although extensive amounts of research have been conducted on soot formation, most of them are concerned with chemical effects and very few actually work with droplet flames. Since combustion is inherently interdisciplinary, involving both the physical processes of heat and mass transport and the chemical processes of reaction kinetics, since droplet flames have very small characteristic scales as compared with other model flames, and since droplet processes are essential to spray combustion, we have systematically quantified the influence of some of the important physical processes on soot formation in droplet burning.

droplet will simply fall into another chilled sampling vial. Considerable experimentations have been performed to validate the viability and accuracy of this sampling probe. Development of this sampling probe has been crucial in the successful execution of several of the following projects.

## 2. Gasification Mechanisms of Multicomponent Droplets

The most important information in multicomponent droplet vaporization and combustion is the sequence and rates with which species of different physical and chemical characteristics are gasified at the droplet surface, because it is only the gasified species which can participate in the gas-phase reaction.

Up until the mid-seventies it was believed that a multicomponent droplet gasified in the manner of batch distillation, which states that the components gasify in the sequence of their relative volatilities. It was, however, subsequently recognized that batch distillation requires an infinitely fast liquid-phase mass diffusivity, although in actuality the diffusivity is extremely slow relative to the other droplet processes. Extensive theoretical efforts have since been expended at developing droplet models which are mass diffusion limited. A particularly important feature of this limit is the possibility that shortly after initiation of gasification, the droplet composition would attain steady profiles, implying the combustion process also becomes steady-state such that the gasification rates of the various components will be proportional to their respective initial concentrations. Such a behavior is obviously qualitatively different from the batch distillation gasification mode.

In order to ascertain the extent of validity of the diffusion-limited mode, we have experimentally determined the variation of the droplet composition of miscible multicomponent fuels during its lifetime. The result



An important consideration here is that in droplet burning soot is formed in the fuel side of the flame. This then implies that the amount of soot formed should be proportional to the dimension of the flame, that soot oxidation is effected as the flame regresses inward and is facilitated as long as the flame forms a closed surface, and that soot emission would be aggravated in the presence of strong convection which causes opening of the flame in the rear wake region through which soot can escape into the ambience without encountering the oxidative barrier imposed by the flame. All of these factors have been experimentally verified.

The experiment also shows that micro-explosion reduces soot formation by a factor around three. We have also explored the merits of blending a sooty fuel by a non-sooty fuel, and found that it is more advantageous to use a non-sooty fuel which is relatively more volatile than the sooty fuel. This is because more soot is formed during the early period of the droplet lifetime because the physical flame size is very large. Thus less soot is formed by having a non-sooty fuel being preferentially gasified during this period.

This work is reported in publication No. 2.

#### 4. Additive Effects on Soot Formation in Droplet Burning

Experimentally it has been demonstrated that soot formation from droplets of heavy oil can be significantly reduced through alcohol blending and water emulsification, although it is not sure what is the dominant factor for such a reduction. There are four potentially important factors: (1) Dilution effect because less sooty fuel is burned per unit mass of total fuel mixture consumed; (2) thermal effect through reduction in the flame temperature because alcohols have lower heats of combustion while water has none; (3) kinetic effect due to the release of the OH radicals from the alcohols and

water in the fuel side of the flame; and (4) Micro-explosion effect as discussed previously. Systematic experimentations have been performed aiming to isolate the various effects through the judicious selection of the mixture components according to their volatility, heat of combustion, the presence of the OH radical, and sooting tendency. Results demonstrate quite convincingly that the primary cause for soot reduction with alcohol blending or water emulsification are compositional dilution and flame temperature reduction, in that order. The results do not seem to suggest any significant catalytic/oxidation effects of the hydroxyl radicals from the fuel mixtures.

This work is reported in publication No. 3

#### 5. Ignition Limits of Droplets Over a Hot Plate

In this project we have experimentally determined the ignition limits of fuel droplets over a hot plate, as functions of the chamber pressure and plate temperature. The practical interest here is droplet ignition by the piston head in direct injection engines. The basic scientific phenomenon involved is that of the Leidenfrost Phenomenon describing the levitation and vaporization of droplets over hot surfaces. It is well known that the evaporation lifetime depends on whether the droplet is in contact with the hot surface and therefore does not vary monotonically with increasing plate temperature. The problem, therefore, becomes quite subtle when this Leidenfrost Phenomenon is coupled to the kinetic process of ignition.

Experimentally we have found that droplet ignition can be achieved only over a particular range of chamber pressure and plate temperature. For low plate temperatures and high chamber pressures, ignition occurs after complete droplet vaporization and the resulting combustion resembles that of a diffusion flame. On the other hand for high plate temperatures and low

chamber pressures, ignition resembles that of thermal explosion. These results can be satisfactorily explained on the basis of Leidenfrost vaporization, the intensity of diffusive and buoyant mixing, and the Damkohler number concept of ignition.

This work is reported in Publication No.4.

#### LIST OF PUBLICATIONS

1. "Liquid-Phase Diffusional Resistance in Multicomponent Droplet Gasification," by A. L. Randolph, A. Makino, and C. K. Law, submitted.
2. "Influence of Physical Mechanisms on Soot Formation and Destruction in Droplet Burning," by A. L. Randolph and C. K. Law, to appear in Combustion and Flame.
3. "Time-Resolved Gasification and Sooting Characteristics of Droplets of Alcohol/Oil Blend and Water/Oil Emulsions," by A. L. Randolph and C. K. Law, submitted.
4. "Pressure/Temperature Ignition Limits of Fuel Droplet Vaporizing over a Hot Plate," by P. Cho and C. K. Law, Int. J. Heat Mass Transfer, Vol. 28, pp. 2174-2176, 1985.

#### PERSONNEL

C. K. Law, Principal Investigator

A. L. Randolph, Ph.D. Student

#### ADVANCE DEGREE AWARDED

A. L. Randolph, Ph.D., Jan. 1986. Currently working in the Engine Research Department of the General Motors Research Laboratories.

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